
# 2016 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

## Multi-Speed Transmission for Commercial Delivery Medium Duty Plug-In Electric Drive Vehicles

Project ID: VS161

**Principal Investigator: Bulent Chavdar**
**Eaton Corporation**
**June 9, 2016**

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# Overview

## Timeline

- Project Start Date: October 1, 2014
- Project End Date: October 31, 2017
- % Complete: 40%

| Budget Period | Start Date | End Date |
|---|---|---|
| 1 | 10/1/2014 | 10/31/2015 |
| 2 | 11/1/2015 | 10/31/2016 |
| 3 | 11/1/2016 | 10/31/2017 |

## Budget

- Project Value: $3,749,710
  - DOE Share: $2,428,655
  - FFRDC: $ 571,100
  - Eaton Share: $ 749,955 ( 20%)
- DOE funding to Eaton: $2,428,655
  - BP1: $ 497,660
  - BP2: $1,171,089
  - BP3: $ 759,906

## DOE objectives

- The public acceptance of electric vehicles will be increased with a transmission
- The performance gap between EVs and ICDVs will be reduced with a transmission
- The concept transmission will be reliable, affordable, scalable and low weight

## Partners

- Prime: Eaton Corporation
- Subcontractors
  - New EV-OEM in BP2. (Smith Electric in BP1)
  - Oak Ridge National Laboratory
  - National Renewable Energy Laboratory

New EV-OEM

# Relevance for addressing barriers

- **Improving the Performance of EVs**

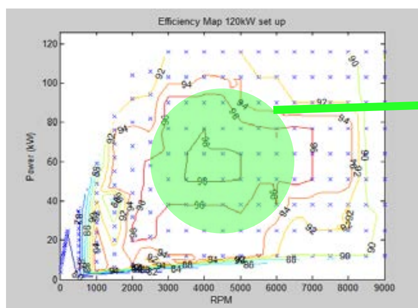
| Characteristic | Units | EV with SS | EV with MS Trans. | Target Improv. |
|---|---|---|---|---|
| Top speed | mph | 55 | 65+ | 20% |
| Efficiency on UDDS | mpge | 29.5 | 32 | 8% |
| Accel. (0-50 mph) | s | 90 | 45 | 50% |
| Gearbox efficiency | % | 93.4 | 98 | 5% |

- **Reliable, efficient, affordable and low weight transmission**
  - Creating and validating a baseline 10 ton medium duty electric truck model.
  - Benchmarking the baseline vehicle performance. Generating transmission concepts and selecting the best concept.
  - Developing cost sensitive, high efficiency transmission by optimizing the number of gears, the gear ratios and the shift strategy.

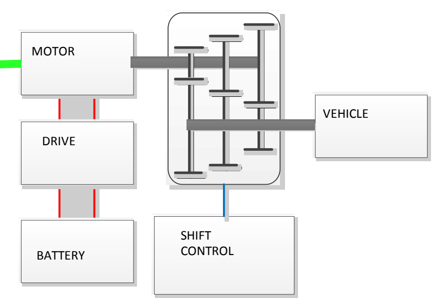
# Approach/Strategy

## Approach: Multi Speed Transmission helps

- Close the performance gap with Internal Combustion Drive Vehicles by operating the motor at its peak efficiency region.
- Provide higher gradeability and faster acceleration with a low gear.
- Increase top speed and range with a high gear.
- By selecting efficient, lightweight, reliable, automated, or automatic transmission concept with novel shifting, clutching and controls systems.




Narrow operating range of motor to the high efficiency region with multi speed transmission




## Strategy

- Customer requirements analysis, system analysis, concept development, designing, prototyping, testing and validation.

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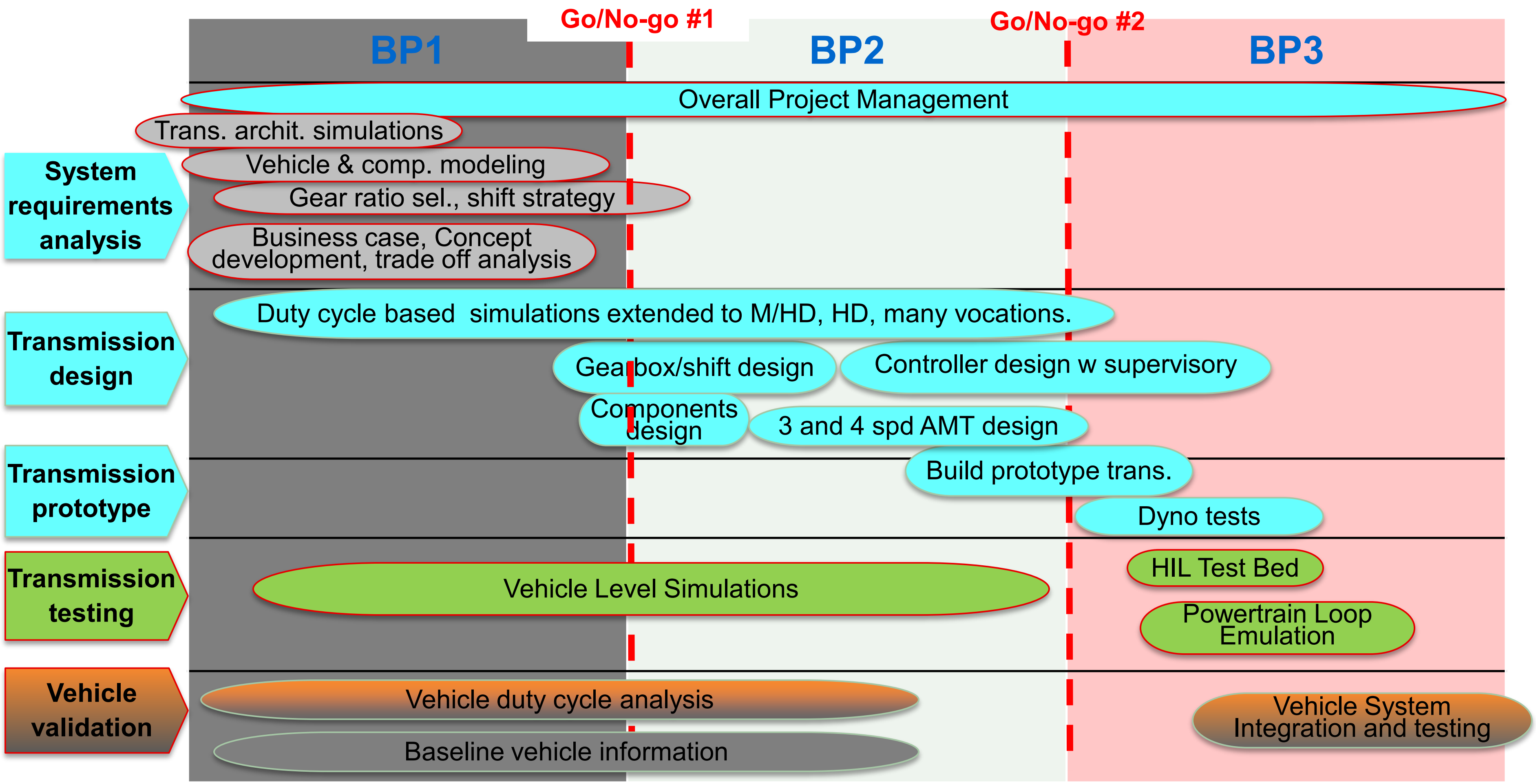
# Re-Scoped Project Plan

Eaton | ORNL | NREL | EV-OEM




- **Go/No-go #1 Preliminary Transmission Design Complete. Concept selected, breadboard transmission selected, performance modeled.** ✓
- **Go/No-go #2 Modular 3 and 4-speed transmission family designed that meets targets and ready to prototype and test.**

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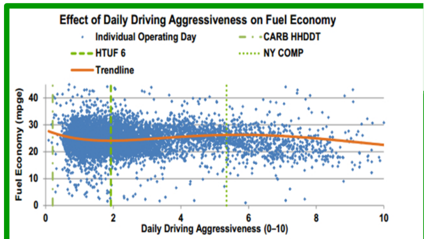
# Milestones, BP2

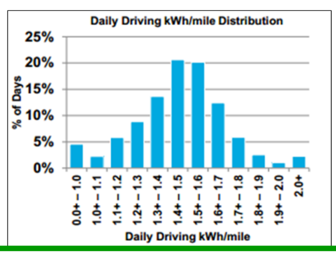
| Date | Milestone and Go/No-Go Decisions | Status |
|---|---|---|
| Jan. 2016 | Milestone<br>Expanded Transmission Modeling/Simulation | Complete |
| Apr. 2016 | Milestone<br>Transmission layout complete | Complete |
| Jul. 2016 | Milestone<br>Transmission system design complete | In progress |
| Oct. 2016 | Milestone<br>1st stage of transmission prototyping complete. | On track |
| Nov. 2016 | Go/No-Go Decision<br>Product intend design is complete | On track |

- **Transmission modeling is extended to other vocations.**
- **Modular 3 and 4-speed Automated Mechanical Transmission (AMT) family will be designed with a flexibility to meet the needs of electric trucks from Class 2b to 7 (or 8500 lb to 36K lb GVW).**

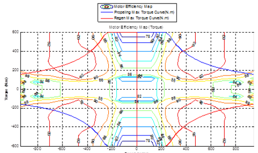
# Technical Progress – Modeling and simulation

## Duty cycles

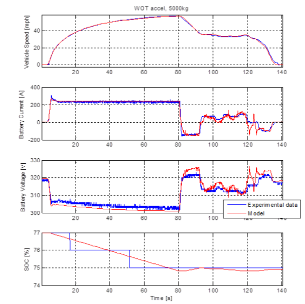


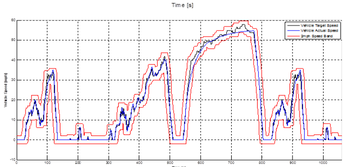




## Vehicle model generation

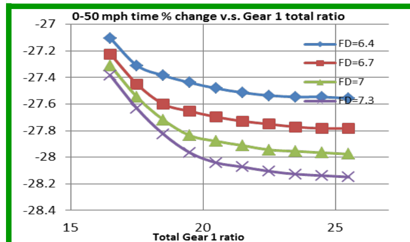


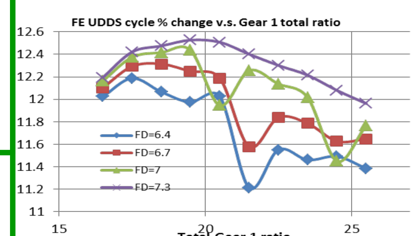

## Vehicle model validation



## Gear Optimization

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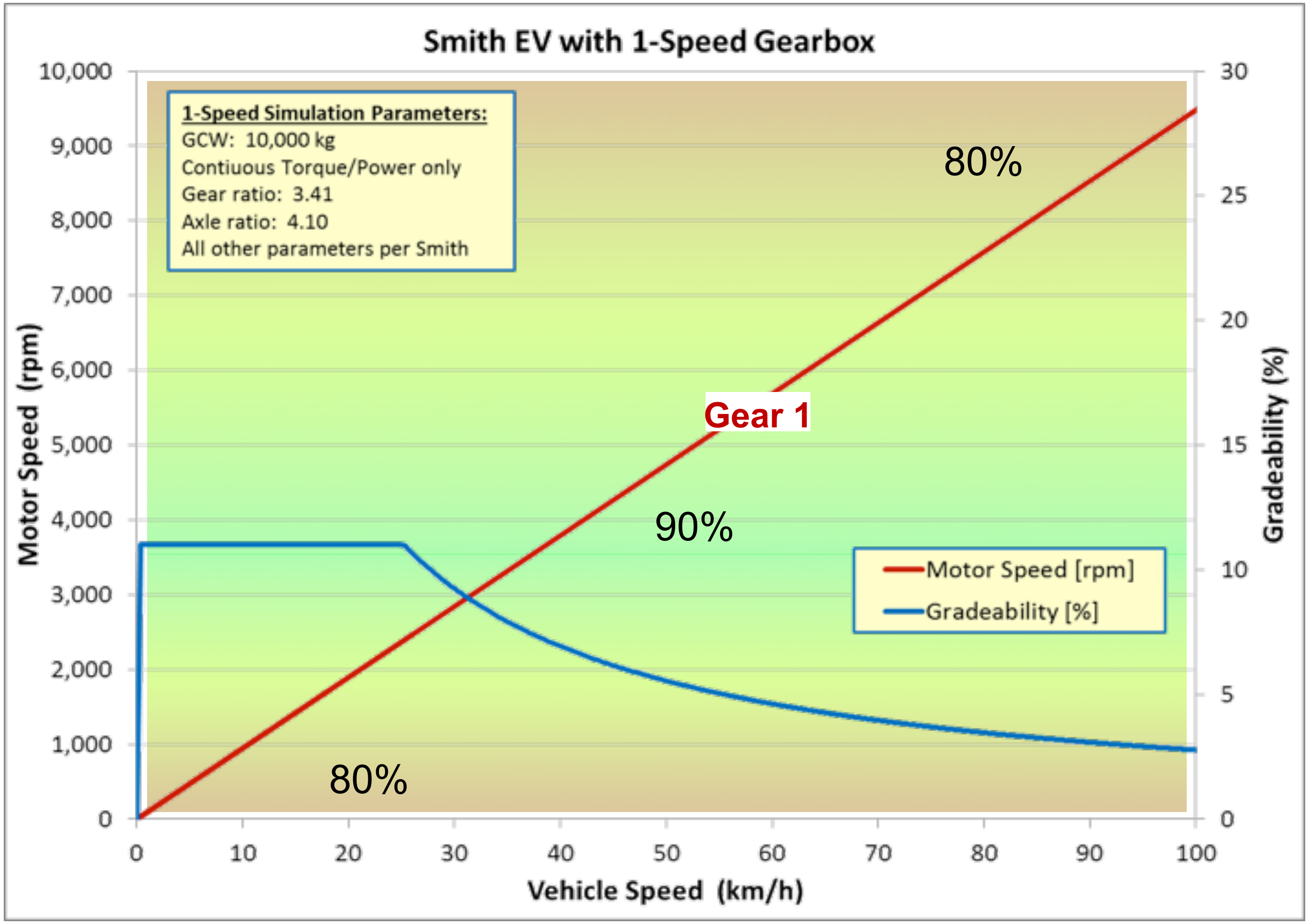
# Technical Progress – EV Powertrain Analysis

## *Single-Speed Transmission*




**Single-Speed: Motor in "Green Band" *only* from 30 to 60 km/h**

20 to 40 mph

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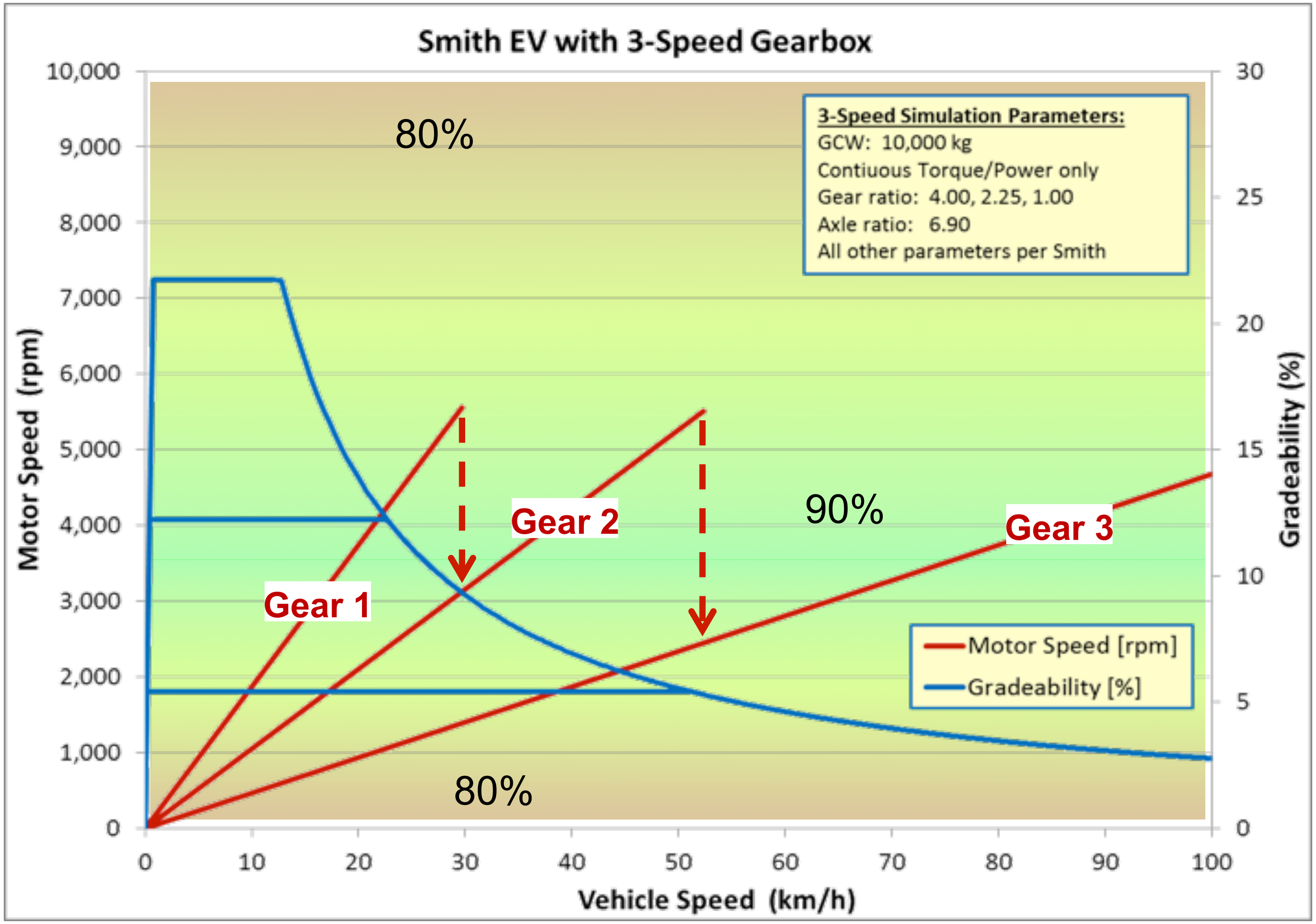
# Technical Progress – EV Powertrain Analysis

## *Three-Speed Automated Mechanical Transmission (AMT)*




**Three-Speed: Motor in "Green Band" from 10 to 110 km/h!**

6 to 70 mph

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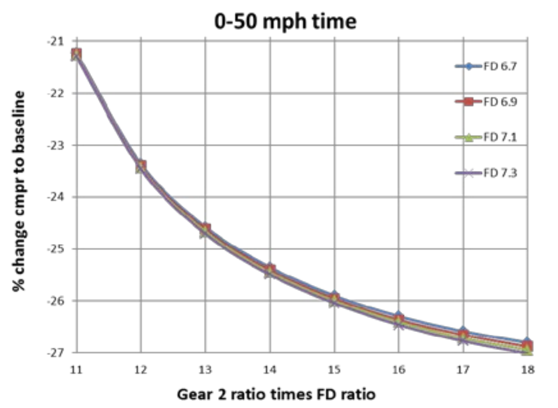
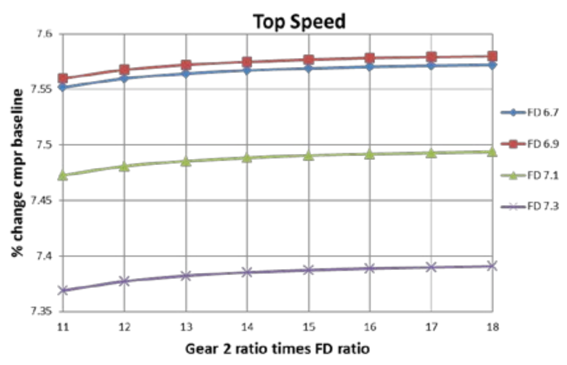
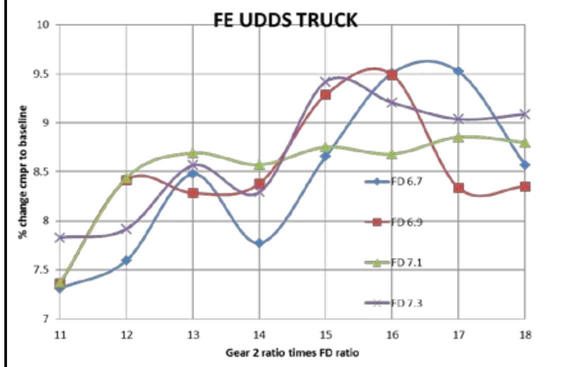
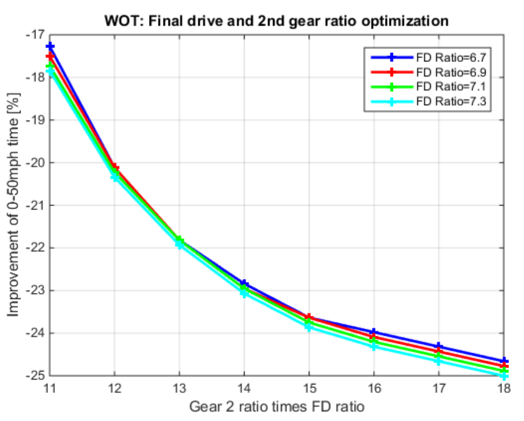
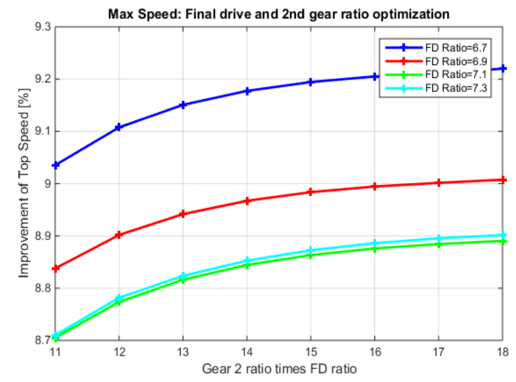
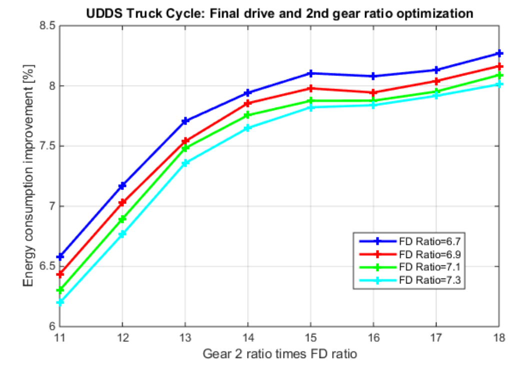
# Technical Progress – Performance with AMT on Smith-Newton™ MD-EV Delivery Truck

| | 0-50 mph Acceleration | Top speed | Efficiency in UDDS |
|---|---|---|---|
| Eaton |  |  |  |
| ORNL |  |  |  |
| | 26% Improvement | 9% Improvement | 8% Improvement |

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# Technical Progress – Gear ratios selection for Smith-Newton™ MD-EV Delivery Truck

**Baseline Smith-Newton™ with SS gearbox:**

**GCW: 10K lb** **SS gear ratio: 3.4**

**GVW: 26K lb** **Final drive ratio: 4.1**

## Recommending 3-speed transmission and a new final drive ratio:

| Gear | Ratio | Benefits |
|---|---|---|
| 1st | 4.0 | Provides 2X torque to the wheels than SS gear. Provides 23% faster acceleration, 8% better efficiency in the 0-10 mph range and 130% higher gradeability than SS gear. |
| 2nd | 2.2 | This ratio is equivalent to Smith's single speed gear box and efficient only at 10-25 mph range. |
| 3rd | 1.0 | Direct drive is the most efficient ratio. Provides 8% better efficiency in the 25 to 65 mph range than SS gear. |
| Final drive | 6.9 | This final drive ratio enables efficient direct drive and 9% higher top speed at the top gear. |

# Technical Progress – EV Transmission

## *Concept Analysis*

- Multiple transmission concepts were developed
- The top 5 concepts were subjected to the trade off analysis based on the performance and business criteria determined earlier in the project.
- The top 5 concepts from high to low ranking:

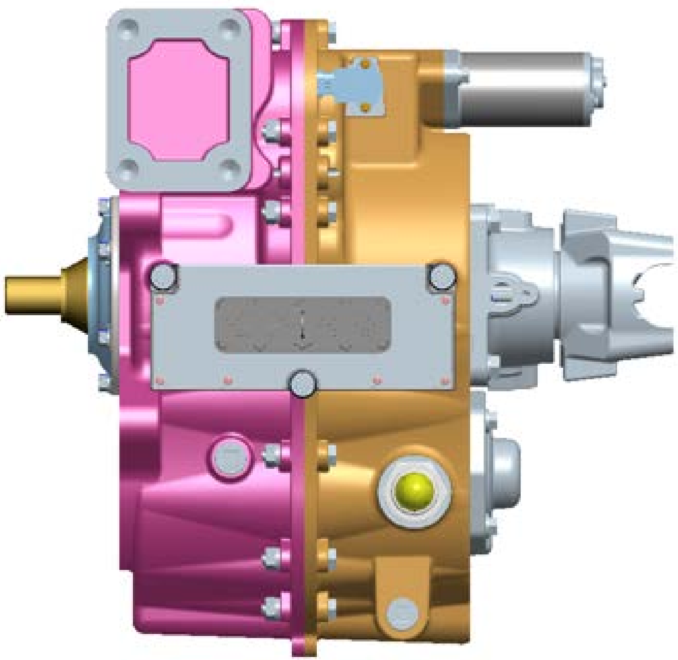
Selected

  - 3-4 speed automated mechanical transmission (AMT) family
  - 4 speed dry dual clutch transmission
  - 4 speed wet dual clutch transmission
  - 3 speed planetary automated mechanical transmission
  - 3 speed planetary powershift transmission

# Technical Progress – 3 and 4 speed AMTs

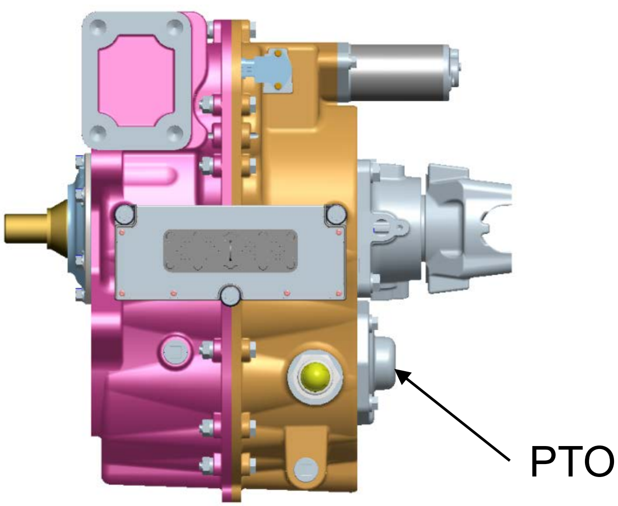
## *Design of Flexible Family of EV Transmissions*

- Up to 1300 Nm (975 lbft), 5000 rpm
- Can be configured as 3 or 4 speed
- Ratio coverage up to 9.0:1
- Flexible design accommodates multiple “gear kits” to cover a wide ratio of vehicle vocations

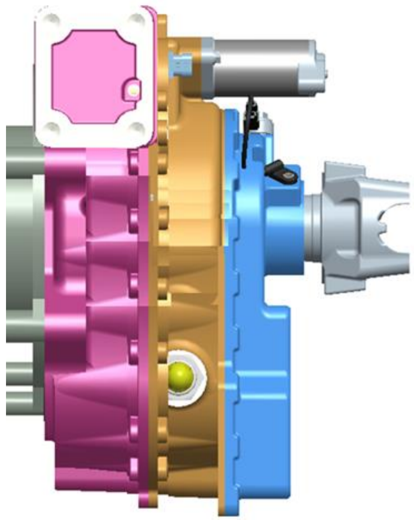


# Technical Progress – Transmission Design

## *Compact 2, 3, and 4 speed EV Transmission Family*



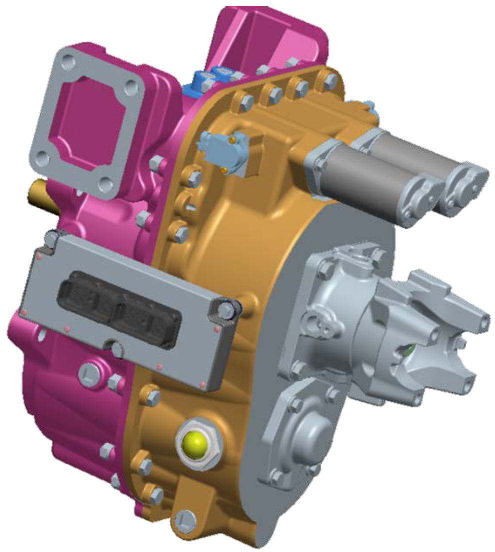

**3 and 4-speed AMTs with rear Power Take Off (PTO) option**



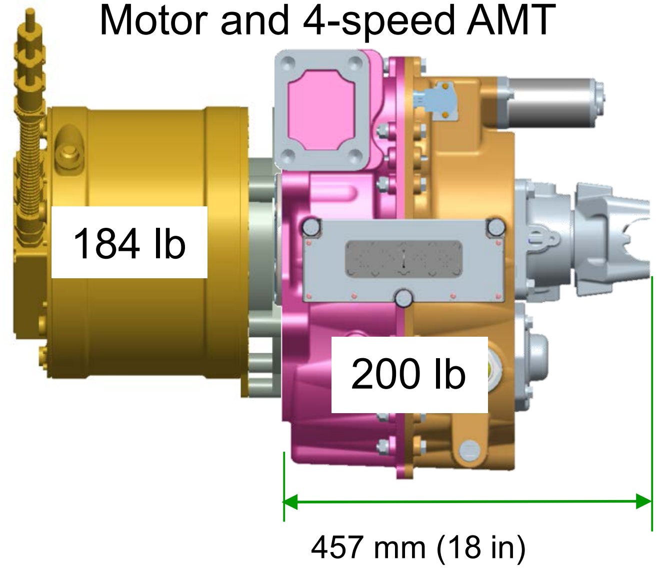
**Concept rendering of 2 speed AMT with dry sump lubrication**

# Technical Progress – Weight and Space claims

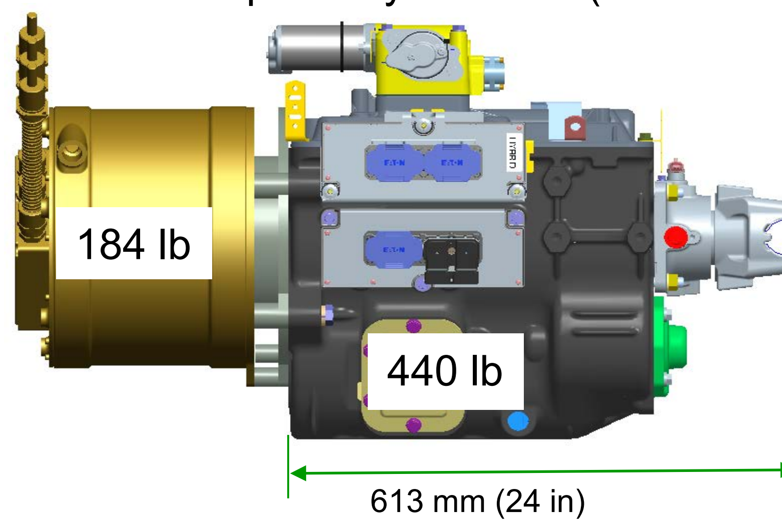
*Comparison of 6-speed (breadboard) and 4-speed AMT*



Motor and 4-speed AMT




Motor and 6-speed Hybrid AMT (Breadboard)

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# Differences Between Original and Rescoped Plans

| | Original Plan Breadboard | Rescoped Plan Product-line-EV-AMT |
|---|---|---|
| Gearbox | 6-speed hybrid gearbox: modified to be 4-speed by blocking out 2 gears | Modular new design: Flexible to create a family of purpose-built 2, 3, or 4-speed EV-AMTs |
| Weight and length | 440 lb, 24 in | 200 lb, 18 in |
| Shifting mechanism | • X-Y shifter<br>• Complex design | • YY shifter: Faster shift; lower cost |
| Materials | • Cast iron housing<br>• Solid shafts | • Aluminum housing - cast or print<br>• Potential hollow shafts |
| Controls | Provide TCM, modify MCU | Provide TCM, modify MCU and supervisory power management of EVs |

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# Responses to Last Year Reviewers' Comments

Question 2: Technical Accomplishments and Progress toward overall project and DOE goals—the degree to which progress has been made, measured against performance indicators and demonstrated progress towards DOE goals.

Reviewer 1:

The reviewer stated that deliverable goals are being met. This is a good topic, but the reviewer questioned the EV volumes in this space and the contribution of such a transmission. The reviewer appreciated Eaton and DOE working on this. The reviewer asked if benefits in acceleration and top speed are really needed. The reviewer understood the increase in gradeability and fuel economy, but questioned the results from voice of customer work shared in Slide 11, and suggested this might be validated a bit more.

- The ranking of performance requirements was based on Smith-Newton-26K-GWV experience. Long acceleration time (88 s for 0-50 mph) and low top speed (50 mph) are barriers to entering a highway for Smith-Newton™ and are the result of restricting the motor to continuous power to extend the range. Since the range has already been maximized and the highway usage is not needed the range and the top speed ranked low for Smith-Newton™. However, the slow acceleration is a major problem even in city driving therefore it ranked very high for Smith-Newton™.
- The requirements will be ranked again after a new EV-OEM partner is selected.

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# Responses to Last Year Reviewers' Comments

Reviewer 3:

The reviewer noted that the approach taken to analyzing EV transmission volume is misleading because one of the keys to see market penetration is the payback period and cost. Only presenting projection on volume is not enough. The reviewer asked what the y axis for the figures in Slide 10 is and what DFSS (Design for Six Sigma) means. The reviewer said do not assume that all readers can understand all acronyms.

The reviewer said if capital cost and price of transmission would be overwhelmingly important (Slide 11), the cost should have been addressed. However, this has not been done yet.

- The market penetration of MD-EVs to a truck market is different from the market penetration of a transmission into an existing MD-EV market. An EV costs twice an equivalent ICDV. A transmission alone will not be able to change this ratio significantly.
- Electric bus market grows in China fast due to the government regulations and the subsidies. A multi-speed transmission enable downsizing the motor thereby being a cost reducer. In other words an EV customer can have performance benefits in addition to the reduced EV price (2.5% less) with a transmission.
- In the case of using the same motor, the pay back period for adding a multi-speed transmission is estimated to be 4 to 8 years based on 10% increase in energy efficiency.

# Collaborations

PRIME

Bulent Chavdar

- Program management
- Requirement definition
- Vehicle system simulations
- Gear ratios and shift strategy
- Transmission architecture
- Controller integration
- Design and prototype
- Component testing
- Vehicle integration
- Commercialization

New EV-OEM

- Requirement definition
- Baseline vehicle
- Performance limits of baseline
- Vehicle integration

**Relationship: Industry**
Subcontractor within VT Program

Oak Ridge National Laboratory

Paul Chambon

- Vehicle level simulations
- Component testing
- HIL testing
- General support

**Relationship: Federal Laboratory**
Subcontractor outside VT Program

National Renewable Energy Laboratory

Adam Duran

- Requirement definition
- Duty cycle harvesting
- Vehicle integration
- Performance testing and demonstration

**Relationship: Federal Laboratory**
Subcontractor outside VT Program

# Remaining Challenges and Barriers

- We need a new EV OEM partner that will contribute to the integration of transmission with the electric vehicle and facilitate the necessary interactions between the transmission controller and the motor controller.
- An integration partner would consist of selecting an eMotor, inverter, and battery supplier then working with each of the suppliers to ensure the respective components meet Eaton's communication specifications.
- Based on the discussions we have been having with EV-OEMs the vehicle integration issues mentioned above may be of low risk.
- By the time of this presentation we may have already found an EV-OEM partner.

# Proposed Future Work

- BP2 – 2016 – Technology Development , Design, and Prototyping
  - Extended transmission modeling and simulations activities
  - Transmission design
  - Prototype fabrication
- BP3 – 2017 – Technology Integration, Testing, and Demonstration
  - Vehicle integration at Eaton
  - Performing preliminary gearbox testing at Eaton
  - Integrated powertrain hardware in the loop testing at ORNL
  - Integrated vehicle testing at NREL

# Summary

- Project is on schedule. All required project milestones have been met to date.
- MD-EVs will benefit from a 3-speed AMT with the following performance improvements based on Smith-Newton™ platform
  - Startability : 130%
  - Acceleration: 23%
  - Top speed: 9%
  - Efficiency: 8% on UDDS cycle
- Supervisory power management is needed to double the improvements on acceleration and top speed on Smith-Newton™.
- Modeling and simulations were expanded to a spectrum of vocations and vehicle segments.
- The initial transmission layout design for a 3 and 4 speed AMT family has been completed.
- The EV-Transmission needs to be low cost, modular, and designed with a flexibility to meet the needs of electric trucks from Class 2b to 7 (or 8500 lb to 36K lb GVW).
- There are opportunities for lightweighting (hollow shafts, aluminum housings), and additive manufacturing technologies.


# 2015 DOE Vehicle Technologies Office Annual Merit

## Technical Backup Slides

"This presentation does not contain any proprietary, confidential, or otherwise restricted information."

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# Technical Progress – Target metrics for Smith-Newton™ MD-EV Delivery Truck

| Characteristic | Units | FOA 10t GVW Baseline with SS | FOA Targets | Project Targets Baseline with MS Trans. | Performance prediction validated by baseline vehicle model at ORNL: Smith 10t GVW Baseline with SS gearbox | Smith 10t GVW Baseline with 3-spd AMT | Improvement |
|---|---|---|---|---|---|---|---|
| Top speed with power limitations<br>without power limitations | mph | 50 | 65+ | 65+ | 54.5<br>59.1 | 59.3<br>70.0 | 8.8%<br>18.4% |
| Energy efficiency on UDDS<br>or range improvement on CILCC | mpge | 37<br>50 | >5% | 8% | 29.6<br>41.7 | 32.1<br>42.9 | 7.7%<br>2.9% |
| Acceleration (0-30 mph) | s | | | 15 | 18.8 | 18.9 | -0.5% |
| Acceleration (30-50 mph) | s | | Increased acceleration | 30 | 69.2 | 48.7 | 29.6% |
| Acceleration (0-50 mph) w pwr limits<br>w/o power limits | s | | | 45 | 88.0<br>25.4 | 67.6<br>24.4 | 23.2%<br>3.9% |
| Gradeability (top speed on 2% grade) | mph | | | | 38.8 | 41.3 | 6.4% |
| Startability (Max. grade on which vehicle launching from rest allows motor to reach max. power in 3 s) | % grade | | Quickly accelerate and climb | 50% improvement over baseline | 9.8% | 22.5% | 130% |
| Reliability (B10 life) | miles | | | | warr. 3yr/36K | 400K | |
| Gearbox efficiency | % | 93.4 | | 98 | 93.4 | 98 | 5% |
| Gearbox weight | lb | | | | 60 | 200 | -333% |
| System weight: gearbox/motor | lb | | | | 244 | 384 | -57% |
| Gearbox dimensions (HxWxL) | in | | | | 14.4x11x9.1 | 21x19x19 | -526% |
| System (G/M) dimensions | in | | | | 18x13.7x20 | 21x19x30 | -243% |

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# Dry-Sump vs Wet-Sump Churning Loss Study

- Eaton's Transmission Descriptive Language tool (TDL) was used to simulate oil churning and calculate losses at various input speeds
- Eaton PS-386 Synthetic Transmission Oil was used for this study
  - Properties were derived at 100˚C
- Five oil levels were studied
  - Studies 3 & 5 were used for wet/dry sump comparisons

Element: Oil - Oil

| Property Name | Value | Units |
|---|---|---|
| name | Oil | - |
| rho | 812.0 | kg/m^3 |
| vk | 14.8 | cSt (mm^2/s) |
| ~~d~~ | ~~0.1149~~ | |
| oilVolume | 0.00535 | m^3 |
| oilLevelToCenterLine | 145.0 | mm |
| ~~cp~~ | ~~2100.0~~ | ~~J/(Kg*K)~~ |

- TDL Oil Inputs:
  - Density (rho)
  - Viscosity (vk)
  - Oil Mass (oilVolume)
  - Oil Level (oilLevelToCenterLine)

| Study # | Oil level (From Center of Main Shaft) | Speed | Churning Losses kW |
|---|---|---|---|
| 1 | Center of Main Shaft - Wet Sump (0 mm) | 1000 | 0.4323 |
| | | 2000 | 1.1052 |
| | | 3500 | 2.212 |
| | | 5000 | 3.4425 |
| 2 | Midway between shafts - Wet Sump (72.5 mm) | 1000 | 0.3024 |
| | | 2000 | 0.7678 |
| | | 3500 | 1.5368 |
| | | 5000 | 2.3917 |
| **3** | **Midway between shafts - Wet Sump (119 mm)** | **1000** | **0.1965** |
| | | **2000** | **0.4924** |
| | | **3500** | **0.9856** |
| | | **5000** | **1.5339** |
| 4 | Center of Counter Shaft - Dry Sump (145 mm) | 1000 | 0.153 |
| | | 2000 | 0.3946 |
| | | 3500 | 0.7898 |
| | | 5000 | 1.2291 |
| **5** | **Bottom of Bearing - Dry Sump (187.5 mm)** | **1000** | **0.0725** |
| | | **2000** | **0.1886** |
| | | **3500** | **0.3374** |
| | | **5000** | **0.5873** |

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# Dry-Sump vs Wet-Sump Churning Loss Study

## *Conclusion*

- **Dry-sump lubrication with oil pump is not recommended**
  - Nominal e-motor operation assumed at 100 kW and 3500 rpm ave.
  - A dry-sump would improve nominal operating efficiency by 0.5%
    - 549 W improvement in loss reduction at nominal operation
  - Minimal efficiency reduction observed does not justify the significant added cost, design complexity, and system risk
  - Eaton’s new PS-386 oil improves gear efficiency while reducing churning loss
- **Wet-sump lubrication**
  - Can adequately dissipate heat (All Eaton MD AMTs use wet sump)
  - 119 mm from centerline of main shaft
  - Total churning losses at nominal speed (3500 rpm): ~1 kW

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